Nuclear Safeguards—

A Global Issue

The location of nuclear power plants, operating, under construction, and planned. Of the 530 units worldwide, 341 are outside the United States; about 230 plants are in operation.

by G. Robert Keepin

Since the dawn of the nuclear age man has experienced varying degrees of both optimism and apprehension about the use and misuse of nuclear energy. This awesome form of energy has provided both an abundant and beneficial source of energy and unprecedented capability for destruction. This basic duality is the driving force behind the unsettled, and still evolving, politics of nuclear energy.

Immediately after World War II, there was hope that placing all nuclear activities under international ownership and management would prevent the proliferation of nuclear weapons. In 1946, the Baruch plan proposed the creation of an international atomic development authority, to be entrusted with all phases of the development, use, inspection, and control of nuclear energy. The plan delineated the need for restraint in nuclear-weapon development and for international safeguards and penalties to prevent diversion of nuclear materials from civilian nuclear power programs. It also proposed that all nations forego the production and possession of nuclear weapons. Although many elements of the Baruch plan were eventually incorporated into international safeguards, in its time the plan was rejected and by 1952, three nations had produced nuclear weapons. Secrecy became the fundamental nuclear policy of the United States and other nations. By the early 1950s, many nations were seeking ways to acquire nuclear technology benefits and to develop their own nuclear energy programs. This activity had an inherent potential not only for peaceful uses but also for military applications. The situation clearly called for renewed attempts to arrive at some form of international understanding, consensus, and constraint.

President Eisenhower's 1953 proposal, the widely hailed "Atoms for Peace" program, marked a fundamental change in US nuclear policy. The program was designed to promote international cooperation in the peaceful uses of nuclear energy and, at the same time, to establish international controls to ensure that the products of this cooperation would not be diverted to military uses.

The Atoms for Peace program was adopted as part of the Atomic Energy Act of 1954. This federal legislation also authorized private ownership of nuclear materials and facilities in the United States and signalled the start of rapid development of nuclear power programs, both domestically and internationally. In 1955, the first United Nations Conference on the Peaceful Uses of Atomic Energy assembled in Geneva, Switzerland. Here, for the first time, scientists from the West and the East met to discuss the technical problems of nuclear energy.

I recall clearly that many of us in the US delegation to the Geneva Conference were filled with a sense of history, and some amazement too, at the open reporting of previously restricted information on fuel-cycle processes and plant operations. Nearly every day, after late-night meetings of the US delegation at the headquarters Hotel du Rhone, we saw new areas of cross-section and fission process data declassified and released to the public. During this historic and unprecedented conference, I could not help but remember my earlier days as a University of Chicago freshman. There, on the way to our freshman calisthenics class under the West Stands of the football stadium, we would occasionally pick up black dust on the soles of our tennis shoes as we passed a sealed-off, heavily guarded area posted with the following warning: US Government Metallurgical Project—Keep Out. As I was to learn years later, the black dust was graphite, the neutron slowing-down or "moderator" material used by Enrico Fermi and his coworkers to achieve the world's first self-sustaining fission chain reaction on December 2, 1942. To me, the unprecedented open spirit of international cooperation that marked the first Geneva Conference was in stark contrast to the wartime secrecy that had of necessity characterized nuclear activities just 13 years earlier in Chicago.

The International Atomic Energy Agency (IAEA), a cornerstone of the Atoms for Peace implementation, was created in 1957 to focus on the promotion and control of the peaceful uses of nuclear energy. From the standpoint of politics and economics, Eisenhower's Atoms for Peace program was more acceptable and far more feasible to implement than the Baruch plan because it did not call for international ownership and management of sensitive nuclear activities. Instead, it proposed a system of *nationally* owned and operated nuclear programs under *international* (IAEA) safeguards inspection and control. Two years before the creation of the IAEA the United States had begun implementing the Atoms for Peace program through "bilateral agreements." Under these agreements the United States provided other nations with nuclear reactors, enriched nuclear fuel, and technical assistance in the development of their civilian nuclear programs. In exchange, these nations accepted bilateral safeguards to ensure the peaceful use of the material and assistance. The United States administered and inspected these safeguards. Establishment of the IAEA in 1957 provided a more acceptable and effective framework for the administration of safeguards agreements than had been possible under the strictly bilateral agreements.

The IAEA's two basic objectives are simple and direct:

The Agency shall seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world. It shall ensure, so far as it is able, that assistance provided by it or at its request or under its supervision or control is not used in such a way as to further any military purpose.

Throughout the 1960s, peaceful nuclear energy programs flourished in many countries because supplier nations, including the United States, offered an extremely attractive, long-term source of nuclear fuel, to discourage the development of other supply sources.

Independently of this peaceful development, France and the People's Republic of China developed and tested nuclear weapons during this period: France in 1960 and China in 1964. These events increased concerns about nuclear weapon proliferation—both the further build up within nuclear-weapon nations and the possession by new nations. In the mid-1960s, intensified efforts to reduce the risk of proliferation culminated in the 1970 Treaty on the Nonproliferation of Nuclear Weapons (NPT), drafted and signed by the United States and the Soviet Union. Nonnuclear-weapon nations that ratify this treaty give up the option to develop nuclear weapons and agree to submit all their nuclear activities to international (IAEA) inspection in exchange for the right to engage in peaceful nuclear activities with the cooperation of the nuclear-weapon nations.

One concept in international relations introduced by the NPT was unprecedented: participating nations committed themselves to international inspections within their boundaries, thereby yielding part of their national sovereignty to an international authority. During NPT negotiations, one concern of the nonnuclear-weapon nations was that applying international safeguards to their activities, and not to comparable activities in the nuclear-weapon nations, would work to their disadvantage in the competitive marketing of peaceful nuclear energy. This problem was partially resolved when the United States and the United Kingdom, by volunteering to place their peaceful nuclear facilities under IAEA safeguards, put both weapon and nonweapon nations on an equal footing. At present, 116 nations, including 3 having nuclear weapons, are parties to the NPT; and 61 nonnuclear-weapon nations have concluded the required safeguards agreements now in force with the IAEA.

The bases for international safeguards on proliferation and diversion of nuclear materials are the NPT, and the IAEA safeguards and inspection system. Other instruments and activities playing a role include the 1967 Treaty for the Prohibition of Nuclear Weapons in Latin America, known as the Treaty of Tlatelolco; the 1976 Nuclear Suppliers Agreements, the so-called "London Club"; and the Nuclear Non-Proliferation Act of 1978.

In the mid-1970s, a broad re-examination of the policies and practices underlying the NPT was undertaken. The re-examination stemmed in part from India's nuclear explosion in 1974 and in part from the concern that the worldwide growth of nuclear power and the reprocessing of spent fuel would make available large quantities of plutonium. Rightly or wrongly, many persons believe that the step from available plutonium to a nuclear weapon is relatively short. This belief leads in turn to the question of whether safeguards inspection and detection systems can provide "timely warning" of plutonium diversion in one nation quickly enough for the international community of nations to take necessary diplomatic actions, including possible sanctions. This line of reasoning resulted in the conclusion that an unacceptable risk of proliferation exists even if the safeguards system could detect diversion at the moment it occurs, and led to the new US position, announced by President Carter in April of 1977. The new position has deferred breeder reactor development, the reprocessing of spent fuel, and the so-called plutonium economy until after evaluation of alternative fuel cycles by the 66-nation International Nuclear Fuel Cycle Evaluation (INFCE) study. After 2 years of extensive effort, the final INFCE report was published in March 1980. Although there are many differences among the INFCE participating nations, a significant degree of consensus was reached on the future directions of nuclear energy. Recognizing the worldwide growth of nuclear energy, the INFCE final summary report calls for continued development of nuclear energy under strengthened nonproliferation measures, and for specific endorsement of plutonium, properly safeguarded, as an important fission energy resource for the future. It was further recognized that countries with large electrical power grids, limited uranium resources, and appropriate experience in nuclear technology will be employing the plutonium-burning fast breeder reactor; accordingly the INFCE report calls for placing the associated sensitive fuel-cycle materials under the most highly effective safeguards and nonproliferation measures.

LASL's Safeguards Program

The safeguards program began at the Los Alamos Scientific Laboratory (LASL) in 1966, at a time when nuclear power programs were expanding in the United States and several other industrial countries at an unparalled rate. After 2 years with the IAEA Headquarters Staff in Vienna, I became convinced of the coming importance—both politically and technically, of the worldwide nuclear safeguards problem. I returned to the United States in late 1965 equally convinced that LASL should launch a vigorous program to develop new nondestructive assay (NDA) techniques and instruments that would in time provide the technical basis for meeting the increasingly stringent safeguards requirements that were inevitable. Following a lengthy series of briefings, hearings, button-holing, and budget reviews with the Atomic Energy Commission (AEC) and the Congressional Joint Committee on Atomic Energy, the nation's first safeguards research and development program was funded and launched at LASL. The program began in a small laboratory at Pajarito Site; as the program grew, this was augmented a year later by the addition of a second, larger laboratory at Ten Site. Six months after the LASL program was launched, the AEC in Washington established the Office of Safeguards and Materials Management as well as a Division of Safeguards in the AEC Regulatory Branch. The Regulatory Branch is now the Nuclear Regulatory Commission (NRC).

Typical of new projects in their early stages, the new safeguards staff at LASL was highly enthusiastic and dedicated to the challenge before us. The LASL Safeguards program got off to a head start in the safeguards field with a commanding lead that I believe has been retained ever since. With the encouragement and cooperation of Dick Baker, Chemistry-Materials (CMB) Division Leader at the time, and the patient tolerance of Bill Maraman and his Plutonium Chemistry and Metallurgy Group, a special technical liaison committee was set up in 1967 between safeguards researchers and the CMB staff. The committee identified needed applications of newly developed NDA technology to materials measurement, accountability, and safeguards problems. Such problems were not uncommon in the materials processing, fabrication, and recovery operations carried out routinely at the CMB plutonium facility. Through the years, the close liaison between safeguards researchers and the CMB staff has contributed significantly to LASL's leadership position in US and international safeguards technology and to LASL's designation as the Department of Energy's (DOE) lead laboratory in safeguards material accountability and control research and development.

Today, the LASL safeguards program encompasses all aspects of the design, development, testing, and in-plant evaluation of new techniques, instrumentation, and integrated systems for safeguarding fissionable materials in all types of civilian and national defense nuclear facilities. These activities involve over 150 staff and support persons mainly concentrated in 7 technical groups: Safeguards Technology, International Safeguards and Training; Detection, Surveillance, Verification and Recovery; Safeguards Subsystems Development and Evaluation; Integrated Safeguards Systems and Technology Transfer; International Safeguards; Analytical Chemistry; and Computer and Telecommunications Security.

Safeguards Objectives—Domestic and International

From the beginning of the US nuclear program, nuclear materials and facilities—in both civilian power and defense-related activities—have been recognized as potential targets for theft, diversion, extortion, and sabotage. Accordingly, a substantial national program of safeguards and security was established early on and has been operational ever since. The goal of the national system is to protect nuclear material in facilities and in transit from subnational threats, such as overt attack by an armed group; from diversion, theft, or other unauthorized activity by facility employees; or from a combination of these "external" and "internal" threats. An external threat—for example, an overt attack by 4 to 8 adversaries armed with automatic weapons, the hijacking of a shipment, or sabotage—is countered by physical protection measures. The more subtle internal threat—covert diversion or theft of nuclear materials—is countered by materials accountability and control systems together with appropriate containment and surveillance measures.

In practice, an integrated system of materials accountability and control together with physical protection is structured to provide, for a given facility, a high-confidence, defense-in-depth safeguards and security system. The record speaks well for the effectiveness of US operational safeguards and security. According to a 1980 Rand Corporation document on threat analysis:

No nuclear installations in the United States have been attacked, seized, or sabotaged in a manner that caused public risk by release of radioactive materials. No nuclear weapons have been stolen or illegally detonated. No nuclear materials have been diverted or taken by force from installations or while in transit and used for blackmail or made into bombs. No radioactive matter has been maliciously released, endangering public safety.

The document also states that, although threats have been made to use nuclear materials, all but one proved to be hoaxes. In the one exception low-enriched uranium was removed from a facility, but was recovered within 3 days, and the thief was apprehended. A few cases of minor sabotage have occurred in the United States and occasional incidents of sabotage or attempted sabotage at nuclear facilities in other countries have been reported in the international press.

Physical protection measures include fences, alarms, the prohibition of unauthorized vehicles, random searches of packages or containers entering secured areas, written records of visitors, DOE clearance requirements, portal monitors to detect illicit movement of nuclear material, dual communications systems for protective force personnel, and response force procedures. Operational procedures, such as the two-man rule, requiring the presence of two cleared persons for access to nuclear materials; special training in emergency procedures; and drills and operational tests of system effectiveness, further support and strengthen the physical protection measures.

NRC regulations for civilian facilities and DOE regulations for government facilities implement material accountability and control in the United States. Under these regulations, measurement and control of special nuclear materials (SNM), such as plutonium and ^{235}U, are typically required to be better than 1%. The control requirement for reactor fuel fabrication plants, for example, is to within 0.5% of plant throughput. For plutonium and highly enriched uranium (enriched to 20% or more in ^{235}U), physical inventories are typically required at bimonthly intervals and/or semiannual intervals. Physical inventories are based on measurements of all material categories including difficult-to-measure scrap and waste, but excluding certain categories of sealed containers and storage vaults. In addition, control and accountability procedures and records must be independently reviewed and audited by NRC or DOE at established intervals.

The concept of "graded" safeguards, used in both domestic and international systems, provides the greatest amount of control and protection to the most sensitive nuclear materials. In the US system, nuclear materials are divided into three categories depending on how difficult it is to convert the material into weapons-usable form. Thus plutonium, highly enriched uranium, and ^{233}U, in the form of metal or pure compounds, such as oxides or carbides, are designated Category I materials; these require the highest priority and most stringent safeguards. Scrap, residues, and mixtures that must be processed, transmuted, or enriched to become usable in an explosive device are designated Category II or III materials, depending on the amount of SNM involved.

In contrast to national safeguards systems, which are designed to counter subnational adversaries, international systems are designed to verify that governments have not used nuclear activities as a source of material for clandestine nuclear weapon programs. The objectives as well as the technical requirements and methods used in the two systems are quite different in some important respects. International safeguards systems are aimed at detecting the diversion of nuclear material to unauthorized purposes and at deterring such diversion by the risk of early detection. While a national safeguards system has the authority and capability to physically protect facilities and material and to recover diverted material, the international (IAEA) system is neither intended to, nor able to, *prevent* diversion. Its main objective is to *detect* discrepancies in inventories and to *deter* diversion by providing a *timely warning* intended to *trigger* international reaction, including possible sanctions.

IAEA safeguards objectives and requirements contain two important quantitative expressions: *significant quantity* and *conversion time.* A significant quantity is the approximate amount of nuclear material, including allowance for loss, deemed necessary to construct an explosive device. Conversion time is the estimated minimum time required to produce the nuclear components of an explosive device. For materials in direct weapon-usable form, such as the metallic state, the IAEA has defined the significant quantity of plutonium and ^{233}U as 8 kilograms and the significant quantity of highly enriched uranium as 25 kilograms. Designated significant quantities are of course larger for low-enriched uranium and for materials in less directly usable forms. Similarly, IAEA has adopted estimated conversion times for different material categories. For example, conversion times for plutonium, ^{233}U, or highly enriched uranium in the metallic form are taken as the order of days (7-10 days), whereas conversion times of oxides or other pure compounds of plutonium, ^{233}U, or highly enriched uranium are taken as the order of weeks (1-3 weeks). The IAEA timely warning criterion requires that the *detection time,* defined as the maximum elapsed time between an indicated diversion and its detection by IAEA safeguards, be less than the estimated minimum conversion time.

In general, international safeguards criteria and requirements are not as stringent as the corresponding national safeguards and security requirements; this is due to the distinctly different objectives of national and international safeguards. In a national system, diversion of a relatively small amount of SNM, such as a threat to disperse 100 grams of plutonium, would be a matter of immediate concern. Thus, performance goals for a national system would typically include the detection of relatively small quantities of SNM in minutes or hours. Likewise, an alarm indicating unauthorized entry into a nuclear facility should bring armed guards to the scene within minutes. The IAEA, on the other hand, does not have the task of prevention or interception of such malevolent acts, or even the detection of such small target amounts of materials in such short times. Instead, the international safeguards system inspector must detect the larger IAEA significant quantities and, depending on the type of material, IAEA detection times may be days, weeks, or months rather than minutes or hours.

Like the record of the US system, the record of the IAEA international safeguards system is indeed reassuring. Thus far, there has been no diversion of nuclear material under IAEA safeguards, and the likelihood of future diversions can reasonably be expected to remain small, in part because of the ongoing operation, and continuous upgrading, of the IAEA system. The IAEA currently carries out some 800 inspections annually in well over 300 facilities around the world having an aggregate of some 70 tons of plutonium, over 10,000 tons of enriched uranium, and 30,000 tons of natural uranium. If one divides the annual IAEA safeguards budget by the kilowatt hours of electricity generated annually in all nuclear power plants, the result is roughly \$0.00002 per kilowatt hour—or about 0.1% of the nominal cost of electricity.

Safeguarding the Nuclear Power Fuel Cycle

According to a recently completed 5-year study by the US National Academy of Sciences (the so-called "CONAES report"), the only choice the United States has to meet large-scale electricity demands for the next 30 years or more is to burn coal and build and operate nuclear power plants. This study of nuclear and alternative energy systems further concluded that nuclear-generated electricity may be the nation's only choice for the 20-year period beginning in 1990. Around that time, operation of coal-burning plants may be curtailed sharply by the future strong demand for coal as a valuable source of synthetic liquid and gas fuels, and by the threat that carbon dioxide accumulation from coal combustion could alter climatic conditions through the heat-trapping *greenhouse effect.*

The CONAES report addressed US domestic energy needs. Similar conclusions on the international level were reached independently by the 66-nation INFCE study, which addressed worldwide nuclear energy needs and fuel-cycle alternatives on a worldwide basis. The INFCE report calls for con-

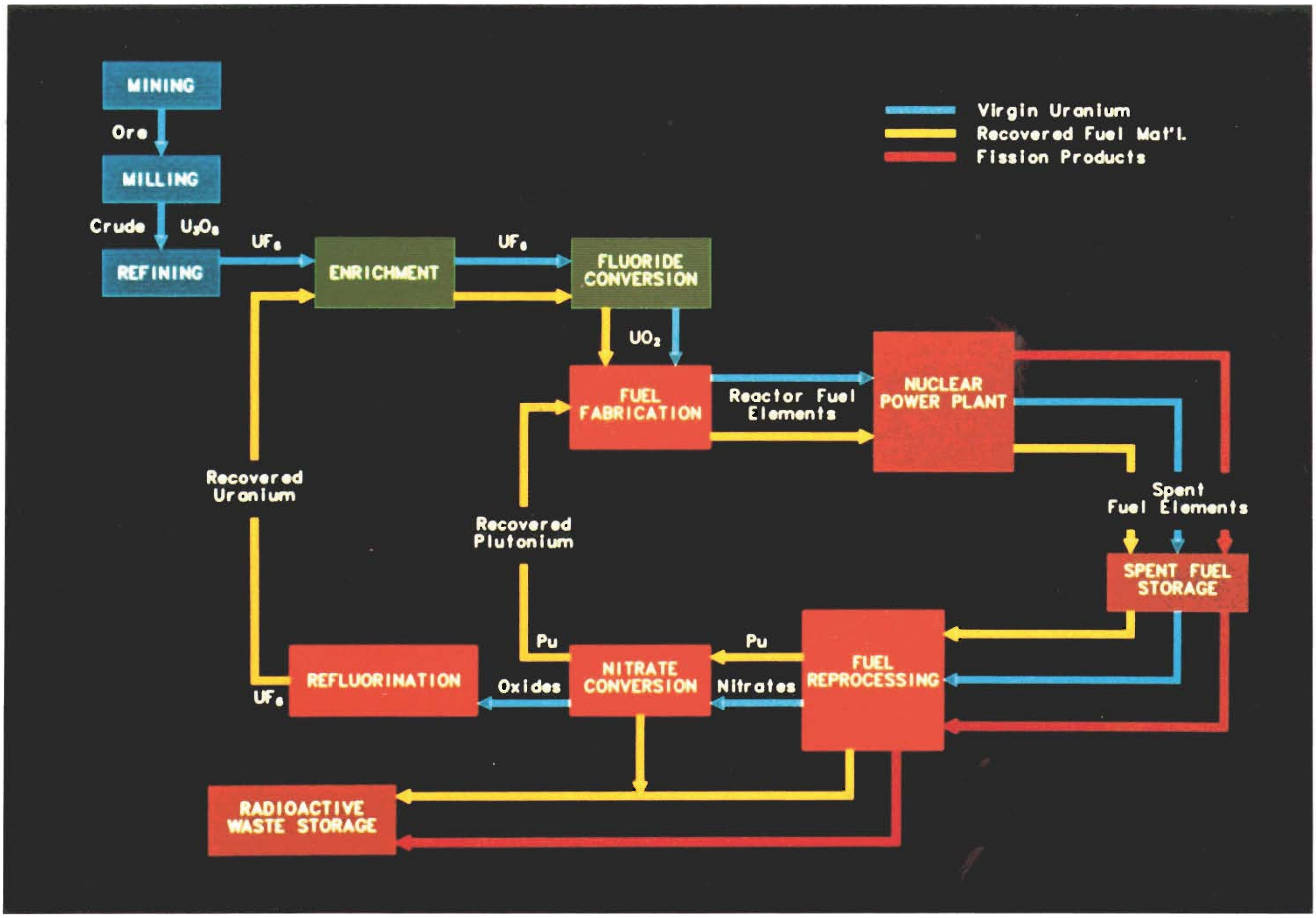


Fig. 1. Power Reactor Fuel Cycle. Uranium ore is mined, milled, and refined, and the resulting U_3O_8 is converted to UF_6 for enrichment to approximately 3% ^{235}U. Reactor fuel, fabricated from virgin, enriched uranium, or mixtures of uranium and plutonium, provides power in the reactor. Spent-fuel elements are stored at reactor sites or at specially designed away-from-reactor storage facilities. In a "once-through" fuel cycle, the spent fuel is stored permanently, and the remaining ^{235}U and the plutonium formed as a by-product of power generation are not used. In a complete fuel cycle, the uranium and plutonium are recovered from the spent fuel and recycled to provide raw materials for new, "mixed-oxide" fuel elements. Safeguards efforts are concentrated on preventing diversion of separated plutonium between the fuel reprocessing and fuel fabrication steps.

tinued development of nuclear power and endorsement of plutonium-based nuclear energy systems, including commercial development of the fast breeder reactor in appropriate countries, in order to avoid a projected shortage of uranium fuel by the end of this century. The INFCE report urged that technical safeguards against proliferation be applied in "a consistent and predictable" (reasonably standardized) way that would not discourage the peaceful development of nuclear energy by creating doubts and uncertainties about the future availability of fuel supplies.

Despite numerous problems and difficulties, nuclear energy is rapidly becoming a major energy source in an increasing number of countries. It currently supplies over 10% of all electric power generated in the United States and 20% or more of total electric power in some industrialized countries, such as Belgium, Sweden, and Switzerland. Some of the more advanced developing countries, such as India and South Korea, have significant and growing nuclear power programs, while many other developing countries are actively seeking to acquire this new source of energy. Recent projections indicate that nuclear power plants will supply nearly one-quarter of the world's electrical energy by approximately the year 2000. As IAEA Director General Sigvard Eklund noted at a recent LASL colloquium, the driving force behind the worldwide growth of nuclear energy is not difficult to understand when viewed against the background of economic, political, and supply-assurance problems associated with the world's shrinking supply of hydrocarbon fuels. With the growing demands for fossil fuel, the cost of oil, for example, has risen by a factor of 5 or 6 in nearly as many years.

Hand in hand with the promise of nuclear energy come some challenging, and recently much publicized, problems and concerns. The accident at Three Mile Island near Harrisburg, Pennsylvania, in 1979, focused worldwide attention on the problems of nuclear reactor safety. TMI also has had

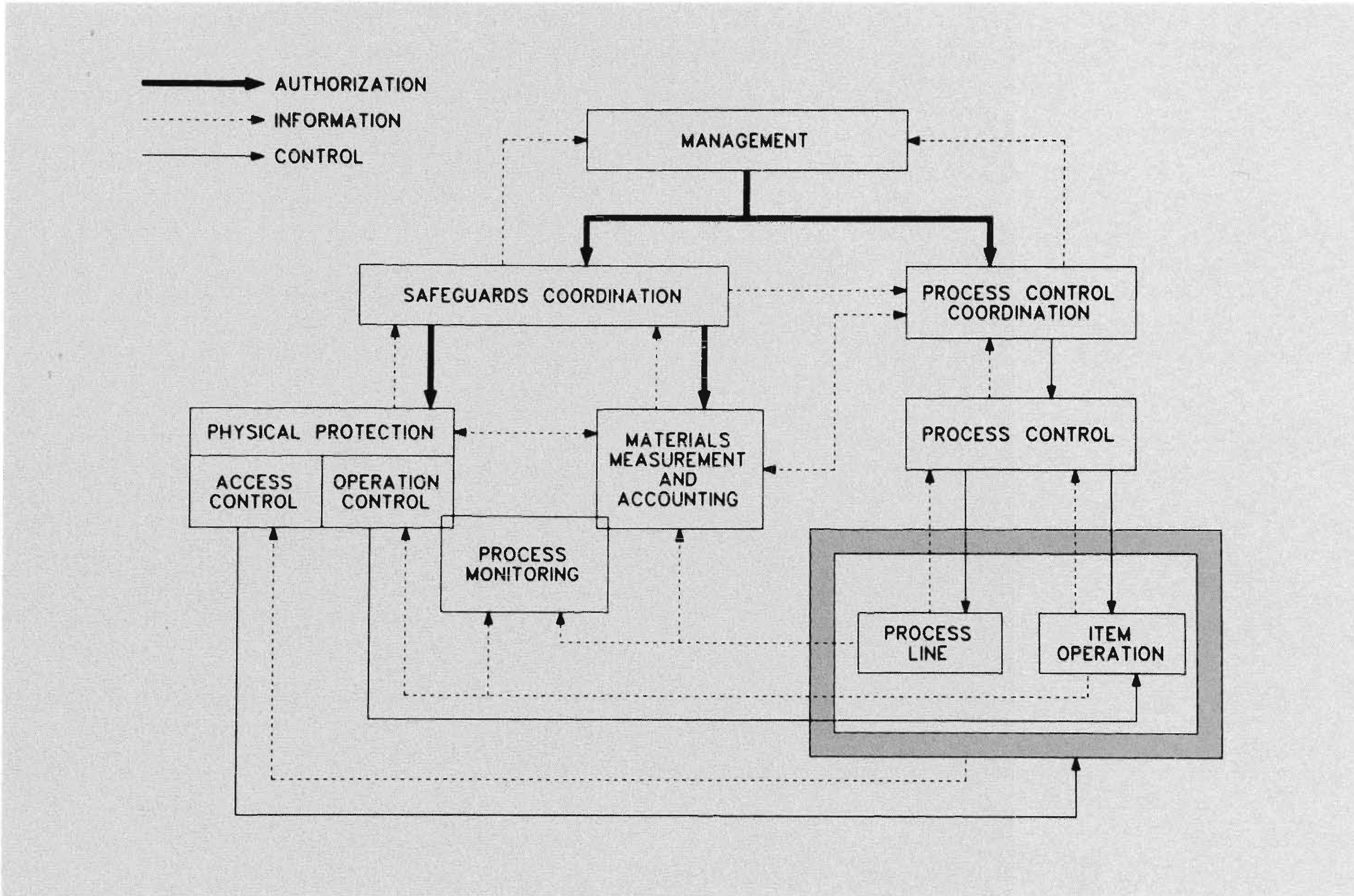


Fig. 2. Structure of the Safeguards System. The functional relationships among the elements of a safeguards system and the normally required management and process control elements of a nuclear fuel cycle facility are indicated by the arrows. Process and item operations are contained within a physical protection barrier (dark outline box) that is part of the physical protection and materials control components of the safeguards system. Materials control is provided by monitoring both the process line and the item operations; the item operations also are controlled. Materials measurements and accounting data are derived from measurements of nuclear materials in process operations. Coordination of each of the components of the safeguards system provides facility safeguards status information to both management and process control coordination.

implications for nuclear energy generally, bringing increased attention to the problems of nuclear waste, weapons proliferation, and nuclear material safeguards. Full realization of nuclear power's great potential for meeting world energy needs will clearly depend on how effectively such problems are addressed, including how effectively nuclear safeguards can be implemented on both the national and the international levels.

During their *lifetime,* nuclear reactor fuel materials undergo a variety of physical and chemical processes in various plants and facilities collectively known as the nuclear fuel cycle (Fig. 1). To maintain strict accountability and control of sensitive fissionable materials throughout the nuclear fuel cycle, we must be able to take a rapid and accurate inventory of these materials in each facility at any given time. This requirement is especially important if a diversion, theft, extortion, or blackmail threat should occur. We must be able to ascertain quantitatively what, where, and how much material is present in any facility at any time. Even more to the point, we must be able to ascertain how much material may be missing from a facility at any time.

Unique Role of Measurement and Accounting Systems

Effective safeguards (Fig. 2) depend on a combination of three basic components: (1) physical protection, (2) materials measurement and accounting, and (3) materials control, including process monitoring. Each component is necessary for a fully effective overall safeguards and security system, but only the materials measurement and accounting component can determine the amount and location of material in a plant at any given time. This capability for determining nuclear material inventories with adequate sensitivity and timeliness provides an overall quantitative check on the combined effectiveness of all other safeguards and security measures at a facility.

Under DOE sponsorship, LASL has developed and demonstrated new automated chemical analysis and NDA instruments that can measure the various forms of nuclear materials rapidly and accurately and thereby provide the high degree of incisiveness required of modern materials measurement and accounting systems. In the application of analytical chemistry methods for safeguards and accountability, it is extremely important to obtain analysis samples that are truly representative of the material being measured. Reliable inventory confirmation further requires precise and accurate analyses of the amounts and isotopic compositions of fissionable materials (uranium, plutonium, and thorium) in widely diverse physical and chemical forms, including pure products, reactor fuels having complex chemical compositions, and numerous types of scrap. Multiphase scrap and materials containing highly refractory components are particularly difficult to dissolve and analyze, while characteristically heterogeneous solid-waste materials in general are simply not amenable to meaningful assay by conventional sampling and chemical analysis techniques.

Major objectives of the LASL analytical chemistry safeguards program are (1) development of fast, effective dissolution techniques and analytical methods for uranium, plutonium, and thorium determinations; (2) design and construction of automated analyzers for these determinations; (3) evaluation of mass spectrometric measurements of uranium and plutonium isotopic distribution; (4) preparation of well-characterized plutonium standard reference materials for distribution by the National Bureau of Standards and for use in DOE safeguards standards intercomparison programs; (5) preparation of plutonium and uranium reference materials for calibration of NDA instrumentation used in the dynamic materials accountability (DYMAC) system at the LASL plutonium processing facility; and (6) participation in an interlaboratory program devoted to measurement of plutonium isotope half-lives.

An example of newly developed automated chemical analysis instrumentation is LASL's automated controlled-potential plutonium analyzer, which determines low-milligram amounts of plutonium with high (0.1%) precision at an average rate of one sample per 30 minutes. The combination of high measurement precision and a specially developed high tolerance for impurity elements makes this relatively low cost analyzer directly applicable to the analysis of a wide variety of nuclear materials.

Because representative sampling of some types of scrap and particularly of heterogeneous solid waste is a particularly plaguing problem, it is not surprising that in the early days of the LASL safeguards program one of the first CMB-identified requirements was for NDA instruments to measure scrap and waste materials. The inherently rapid NDA methods also offered the capability for measuring essentially every individual contained unit of feed or product material. For example, in the assay of reactor fuels, NDA techniques made it possible to measure the total fissionable material loading of each individual reactor fuel rod and to certify, on a routine production basis, the pellet-to-pellet uniformity of uranium fuel loading. Such certification of uniform loading is an important quality control factor in avoiding "hot spots" in the fissioning fuel, and thereby also an important factor in reactor safety. Other "spin-off" benefits of modern nondestructive and destructive measurement techniques developed for safeguards include better in-plant process control, quality assurance, operational safety, and more efficient management of recycle and waste materials.

Major goals for acceptable performance of NDA instruments were set forth in the period from 1965 to 1970, concurrent with steadily increasing pressures to rigorously quantify and reduce uncertainties in measured nuclear material inventories. Characteristic measurement times for individual items were usually under 10 minutes and desired accuracies for the various material categories were 0.2-3.0% for well-characterized, uniform feed and product materials; 2-10% for recoverable scrap materials; and 5-30% for poorly characterized nuclear waste.

Fissionable nuclide characteristics exploited for "passive" assay are the gamma-ray, neutron, and alpha-heat emissions accompanying the natural radioactive decay of the nuclides. Supplementing passive NDA techniques, "active" assay methods use external neutron sources to induce fissions in a sample; the fissions are then measured by counting fission neutrons or gamma rays. Gamma-ray and x-ray densitometry also provides rapid, accurate determination of the concentrations of uranium, plutonium, and thorium in typical solutions and solids.* The principal neutron and photon measurement techniques and instruments currently in use or being developed for measuring fuel-cycle materials are summarized in Tables I and II. Calorimetry, a technique based on the measurement of radioactive decay heat of contained materials, also has been implemented widely for measurement of plutonium.

Advanced Materials Accountancy and Control

In conventional safeguards practice, the accountability of nuclear materials within a facility and the detection of unauthorized removals have relied almost exclusively on discrete-item counting (as opposed to the more difficult task of measuring bulk process materials) and on material-balance accounting following periodic shutdown, cleanout, and

*See "Nondestructive Assay for Nuclear Safeguards," in this issue.

TABLE I
GAMMA- AND X-RAY ASSAY SYSTEMS

Instrument or Technique	Operating Principle	Application
Segmented gamma scanner[a]	Passive gamma-ray analysis; transmission of external source gammas used for attenuation correction	Quantitative assay of ^{239}Pu, ^{235}U in scrap and waste
MEGAS[a]	High-sensitivity passive x- and gamma-ray detection	Screening of low-density transuranic waste at the 10 nCi/g fiducial
Gamma-ray spectroscopy[b]	Passive gamma-ray analysis with Ge or NaI detectors; sometimes augmented by measurement of transmission of external source photons	Assay of U, Pu; Pu isotopic analysis; U enrichment
X-ray edge densitometry[b]	Photon transmission in the region of L_{III}- or K-edges	Elemental concentrations of Th, U, Pu
XRF[b]	X-ray fluorescence	Elemental analysis of Th, U, Pu

[a]Well developed for many fuel cycle applications; instruments commercially available.

[b]Developed for some fuel cycle applications and being evaluated for others.

physical inventory. The classical materials balance usually is drawn around the entire facility or a major portion of the process. It is formed by adding all measured receipts to the initial measured inventory and subtracting from this sum all measured removals and the final measured inventory. During routine production, material control is vested largely in administrative and process controls, augmented by secure storage for discrete items and sealed containers.

Although periodic shutdown-cleanout operations will always be important in determining the amount of bulk nuclear material holdup in process equipment, pipes, pumps, traps, and filters, the use of this procedure alone has inherent limitations in sensitivity and timeliness. Sensitivity is limited by measurement uncertainties that might obscure the diversion of relatively large quantities of SNM in a large throughput plant. Timeliness is limited by the practical difficulties, the expense, and hence the infrequency of process shutdown, cleanout, and physical inventory; thus a loss of material could remain undiscovered until the next physical inventory.

Recently developed NDA technology, state-of-the-art conventional (destructive) measurement methods, and special inplant sensors, combined with computer and data-base management technology, provide the necessary technical basis for much more effective methods of safeguarding nuclear facilities. For example, the greater sensitivity and timeliness requirements on SNM control now being imposed by DOE and NRC can be achieved by subdividing a nuclear facility into discrete accounting envelopes, called unit processes, and drawing individual material balances around them. A unit process is chosen on the basis of process logic, the time material resides within the unit process, and the ability to perform quantitative measurements and draw a material balance. Thus, by subdividing a facility into unit processes and measuring all material flows across unit process boundaries, the

TABLE II

NEUTRON ASSAY SYSTEMS

Instrument or Technique	Operating Principle	Application
Random driver[a]	Am-Li source neutrons; fast coincidence detection of prompt neutrons	Fissile assay of Pu and highly enriched U; passive assay of ^{240}Pu and ^{242}Pu
^{252}Cf shuffler[b]	Cyclic irradiation with moderated ^{252}Cf neutrons; detection of fission delayed neutrons	Fissile assay of a wide range of U, Pu material categories
^{252}Cf fuel rod scanners[a]	Irradiation with moderated ^{252}Cf neutrons; detection of fission prompt neutrons, delayed neutrons, or delayed gamma rays	Fissile assay of FBR, LWR fuel rods
Antimony-beryllium[b]	Irradiation with Sb-Be photoneutrons; integral counting of fission prompt neutrons	Fissile assay of cold and spent fuels
Thermal-neutron coincidence counter[a]	Time-correlated detection of spontaneous fission neutrons with polyethylene-moderated ^{3}He well counter	Assay of ^{240}Pu, ^{242}Pu, and ^{239}Pu

[a]Well developed for many fuel cycle applications; instruments commercially available.

[b]Developed for some fuel cycle applications and being evaluated for others.

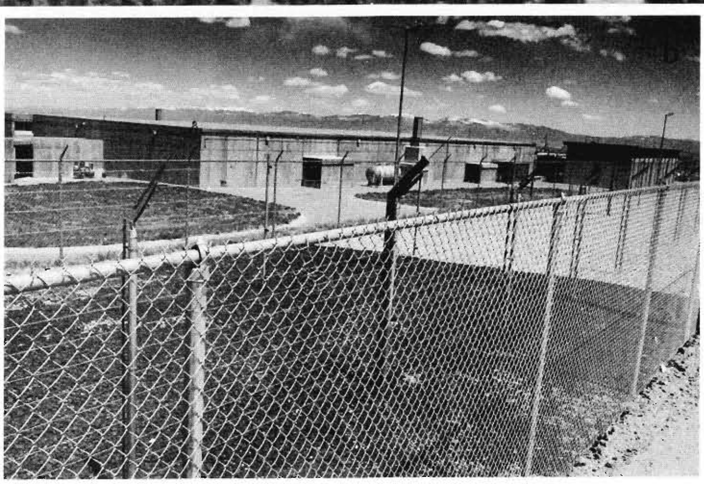
location and movement of all SNM can be localized in both space and time. Materials balances drawn around unit processes are called *near-real-time* or *dynamic* materials balances to distinguish them from conventional balances drawn after a shutdown, cleanout, and physical inventory.

In a direct application of the foregoing general principles, LASL is integrating newly developed NDA technology with automated data processing, monitoring and surveillance techniques, modern data base management, and decision analysis methods into an overall dynamic materials accountability system, called DYMAC. The system provides direct in-plant implementation of modern near-real-time accountability and control. A specific application of the DYMAC concept and associated safeguards technology at the LASL plutonium processing facility is shown in Fig. 3. To date, the DYMAC system at the LASL plutonium facility has completed over 100,000 material transactions with no significant errors or discrepancies.

The least disruptive time to develop and evaluate new safeguards systems designs is before a facility is built, preferably at the conceptual-design stage. Accordingly, the LASL safeguards program has developed and evaluated conceptual designs of cost-effective integrated systems for most fuel-cycle facility types. Concepts, design criteria, and recommendations from the LASL effort are being increasingly implemented both domestically and internationally.* In addition, advanced materials accoun-

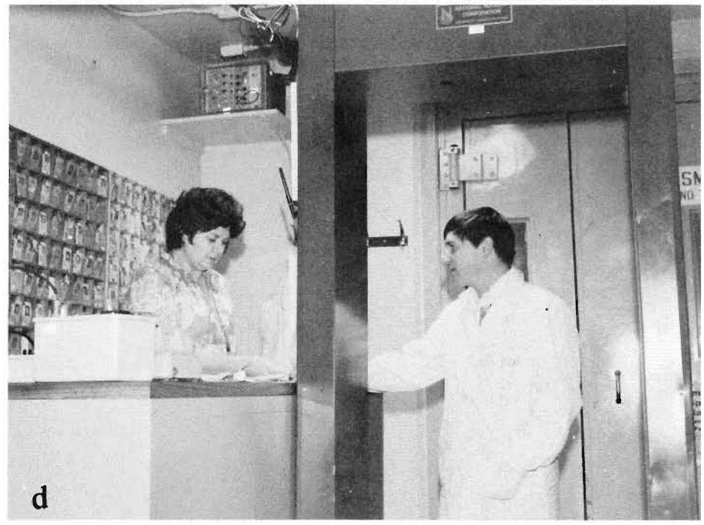
*See "Dynamic Materials Accounting Systems," in this issue.

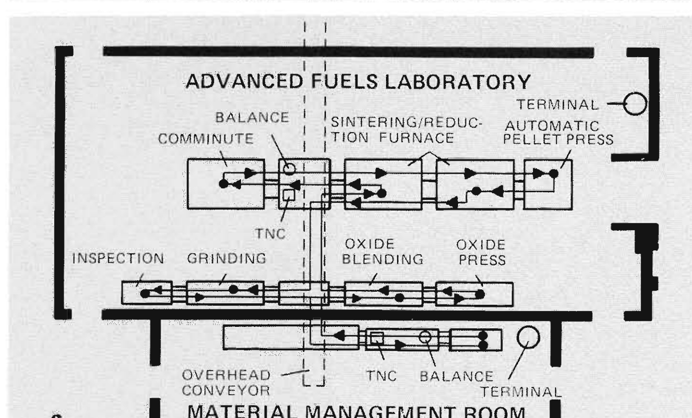
Fig. 3. Safeguards at the Plutonium Processing Facility



(a) The new LASL Plutonium Processing Facility is the large concrete structure in the left half of the photograph. Many proven security measures including fences, limited access, and alarms are employed to safeguard the facility. Other measures are so new they are in the demonstration stage, such as DYMAC, the dynamic materials accountability system that keeps track of the facility's inventory of nuclear material. Processing operations began here in January 1978. The facility now has over 6000 inventory items to safeguard.

(b)To study the effectiveness of various types of perimeter fences and intrusion devices, Sandia Corporation recently erected a 100-meter-long test bed outside part of the existing perimeter fence at the plutonium facility.





(c) Security guards inspect all items that persons carry into the facility grounds and search vehicles entering and leaving the grounds with portable gamma meters developed at LASL.

(d) The two main entry points into the processing building are manned stations where persons exchange badges and pass through commercially available portal monitors, which detect radiation. The performance of the portal monitor is being evaluated.

(e) Inside the facility's vault, all items are stored in containers that have individual seals. Some of the vault spaces have LASL-developed shelf monitors that can detect whether a container or part of its contents has been removed.

(f) The Advanced Fuels process, one of 23 processes currently operating in the plutonium facility, produces fuel pellets for the FFTF (fast-flux test facility) reactor in Richland, Washington. The process constitutes one accountability area, within which seven subareas have been defined, each corresponding to a particular step in the fabrication process. A materials balance can be drawn around the entire process and around each subarea to determine exactly how much plutonium is present and where it is located.

(g) A technician uses a microprocessor control unit to control operation of the thermal neutron coincidence counter on top of the glove-box line. She is measuring the amount of plutonium in a batch of finished fuel pellets for a materials balance.

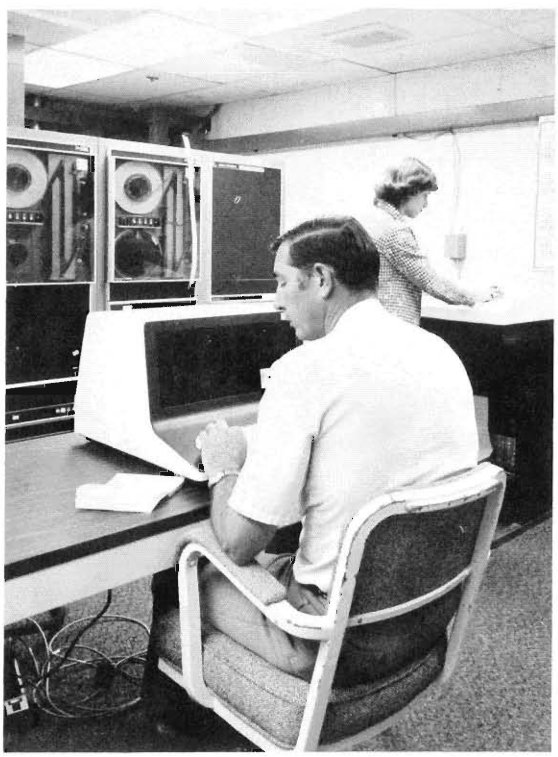
(h) Following the measurement of finished fuel pellets, a technician makes a transaction to update the computer inventory with the correct amount of plutonium contained in the pellets.

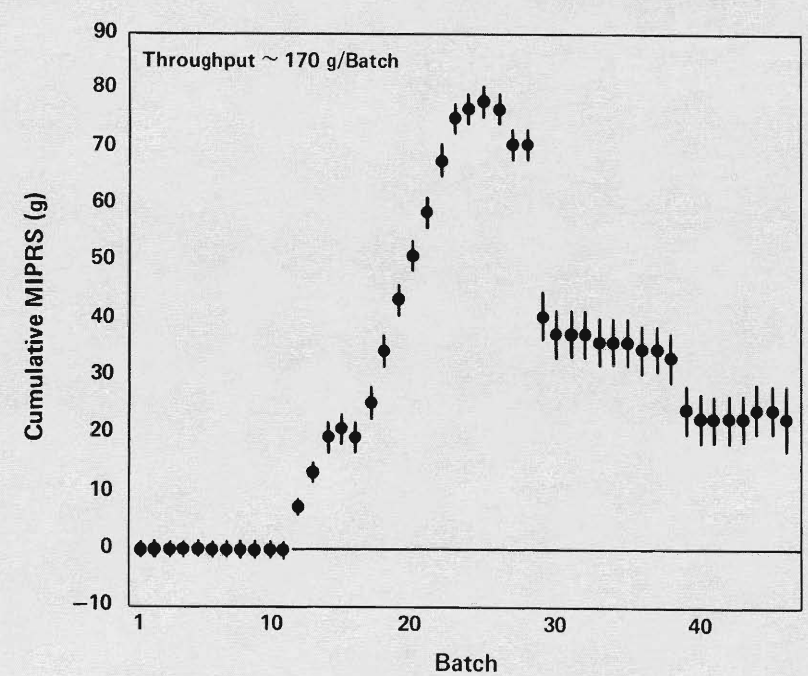
(i) The central computer keeps track of the facility's inventory. It accumulates, sorts, and stores the information from individual transactions, and makes it available to any authorized requestor at a terminal. Programmers and computer operators in the DYMAC computer room keep a constant check on the system to make sure it is operating properly.

(j) A materials balance is the difference between material introduced into a unit process and the material removed from the process. Results of material balancing for the sintering/reduction furnace in the Advanced Fuels process is shown on an MIP (material-in-process) chart. Small amounts of plutonium accumulate on the boats that transport the pellets into the furnace. The chart indicates the amount of plutonium that each batch contributes to the MIP buildup on the boats. When the MIP grew to about 80 g, the supervisor conducted a cleanout to recover as much plutonium as was practical. The plutonium recovered from the boats was measured with the thermal neutron coincidence counter and sent to scrap recovery.


g


h




Throughput ~ 170 g/Batch
Cumulative MIPRS (g)
90
80
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j

tability and control systems, many quite similar to DYMAC, are being tested and evaluated at a number of nuclear facilities in the US and abroad. As these in-plant test and evaluation programs are completed, the resulting technology and operational experience will be available for introduction into various types of domestic and international fuel-cycle facilities.

Emergency Response and Recovery

Its excellent record notwithstanding, if a safeguards system should fail and nuclear materials are missing from a facility, there must clearly be a demonstrated response capability to recover materials rapidly, and to apprehend the offender. Likewise, an emergency response plan and demonstrated field-operational capability is essential in responding to nuclear emergencies, accidents, acts of terrorism, blackmail, and sabotage. LASL's special qualifications and experience in both national defense programs and safeguards technology provide a unique capability for innovative design and development of instrumentation for surveillance and search-and-recovery applications. This capability includes the design of hand-held monitors for searching personnel and vehicles at facility-access areas and the development, testing, and evaluation of SNM portal monitors, vault monitoring systems, and enclosure detector arrays. It also includes passive and active NDA techniques for SNM identification and verification as applied, for example, to a variety of thorny problems that arise in safeguarding SNM movements into and out of a rigidly proscribed "perimeter" around sensitive technology areas in domestic or international fuel-cycle facilities, or in safeguarding defense-related activities and facilities.

A major component of emergency-response capability is the NEST—Nuclear Emergency Search Team—activity. This program provides emergency response to incidents of nuclear extortion, nuclear weapon accidents, lost or stolen nuclear materials, and terrorist threats. Portable and mobile nuclear detection systems having high sensitivity and real-time data processing and analysis capability have been developed and deployed for field test, evaluation, and operational use. A related effort involves the development and field testing of instrumentation and procedures for detection, diagnosis, and disabling of improvised or otherwise unknown nuclear devices. Suffice it to say, these efforts require extensive coordination with other DOE laboratories and federal agencies, primarily the FBI and the Department of Defense, all of whom share with LASL major responsibilities in the nation's emergency response system.

The 1980s as the Decade of Technology Transfer

If the 1970s can be regarded as the decade of modern safeguards technology development, the 1980s must be the decade of the transfer of this technology to nuclear facilities—both existing and new. As indicated in Table III, interactions between the LASL program and nuclear facilities of all types, in both the government and private industry sectors, involve the gamut of safeguards R&D activities from instrument development, calibration, test, and in-plant evaluation to the design, optimization, and performance analysis of overall facility safeguards systems. On the international level, there is growing interest, particularly among other industrialized nations, in the design, optimization, and practical in-plant implementation of integrated safeguards systems incorporating state-of-the-art materials

TABLE III

LASL INTERACTION WITH US FUEL CYCLE FACILITIES

Fuel Cycle Facilities	MC&A[a] Systems Studies	Location for Test and Evaluation of NDA Instrument	Process Info to LASL	LASL Instrument Specs to Vendor or Facility	Training	Consultation
Fuel Fabrication						
Westinghouse Corporation	●	●	●	●	●	●
General Atomic Company		●	●	●	●	●
General Electric Corporation		●	●	●	●	●
Nuclear Fuel Services			●	●	●	●
Babcock & Wilcox				●	●	●
Spent-Fuel Reprocessing						
Allied-General Nuclear Services	●		●	●	●	●
INEL, Idaho Falls		●	●		●	●
Oak Ridge National Laboratory	●		●	●		●
Savannah River Plant	●	●	●		●	●
Nitrate-to-Oxide Conversion						
Allied-General Nuclear Services			●	●	●	●
Savannah River Plant	●	●	●		●	●
General Electric Company	●		●		●	●
Rocky Flats Plant			●	●		
Waste Handling and Solidification						
Allied-General Nuclear Services			●		●	●
SROO-SRL	●		●		●	●
INEL, Idaho Falls			●	●	●	●
Rockwell, Hanford			●	●	●	●
Uranium Enrichment						
Union Carbide	●	●	●	●	●	●
Goodyear Atomic		●	●	●	●	●
TRW	●		●			●
LLL, Livermore	●		●			●
Critical Facilities						
Argonne National Laboratory	●	●	●	●	●	●
Nuclear Instrumentation Vendors				●	●	●

[a]Materials control and accountability.

measurement and accountability technology, materials control, and physical security including effective use of containment and surveillance techniques.

A major component of effective technology transfer is education and training in the use of modern NDA instrumentation and information-handling and analysis systems. The entire area of safeguards professional training has received marked impetus from the Three Mile Island nuclear reactor accident and the resultant three main "lessons learned": the need for (1) better professional training of reactor operators, (2) better measurement instrumentation, and (3) better emergency response. One notable example of the effective transfer of modern safeguards technology to plant operators and safeguards inspectors alike is DOE's ongoing Safeguards Technology Training Program conducted by LASL through four separate course offerings per year:

1. **Fundamentals of Nondestructive Assay of Fissionable Material Using Portable Instrumentation.**
2. **In-Plant Nondestructive Assay Instrumentation (to be succeeded in 1981 by a course on advanced instrumentation based on neutron detection methods).**
3. **Gamma-Ray Spectroscopy for Nuclear Materials Accountability.**
4. **Advanced Systems for Nuclear Materials Accounting.**

These training courses attract well over 100 participants annually. Participants from the United States represent both the government and private sectors and those from the IAEA inspectorate represent a large number of countries around the world.

Technology transfer and assistance to the IAEA encompasses not only development, test, and evaluation of instruments, but also personnel training (of highest priority to IAEA), technical consultation, and direct assistance to the IAEA safeguards staff by visiting consultants and resident experts on loan from member states. Two examples are US participation in the IAEA International Working Group on Reprocessing Plant Safeguards and in the IAEA Advisory Group on Fuel Element Fabrication. Both groups are concerned with the application of IAEA safeguards to the advanced large-scale fuel-cycle facilities that are foreseen for the future. Four LASL safeguards staffers are currently assigned to the IAEA Department of Safeguards at Agency headquarters in Vienna.

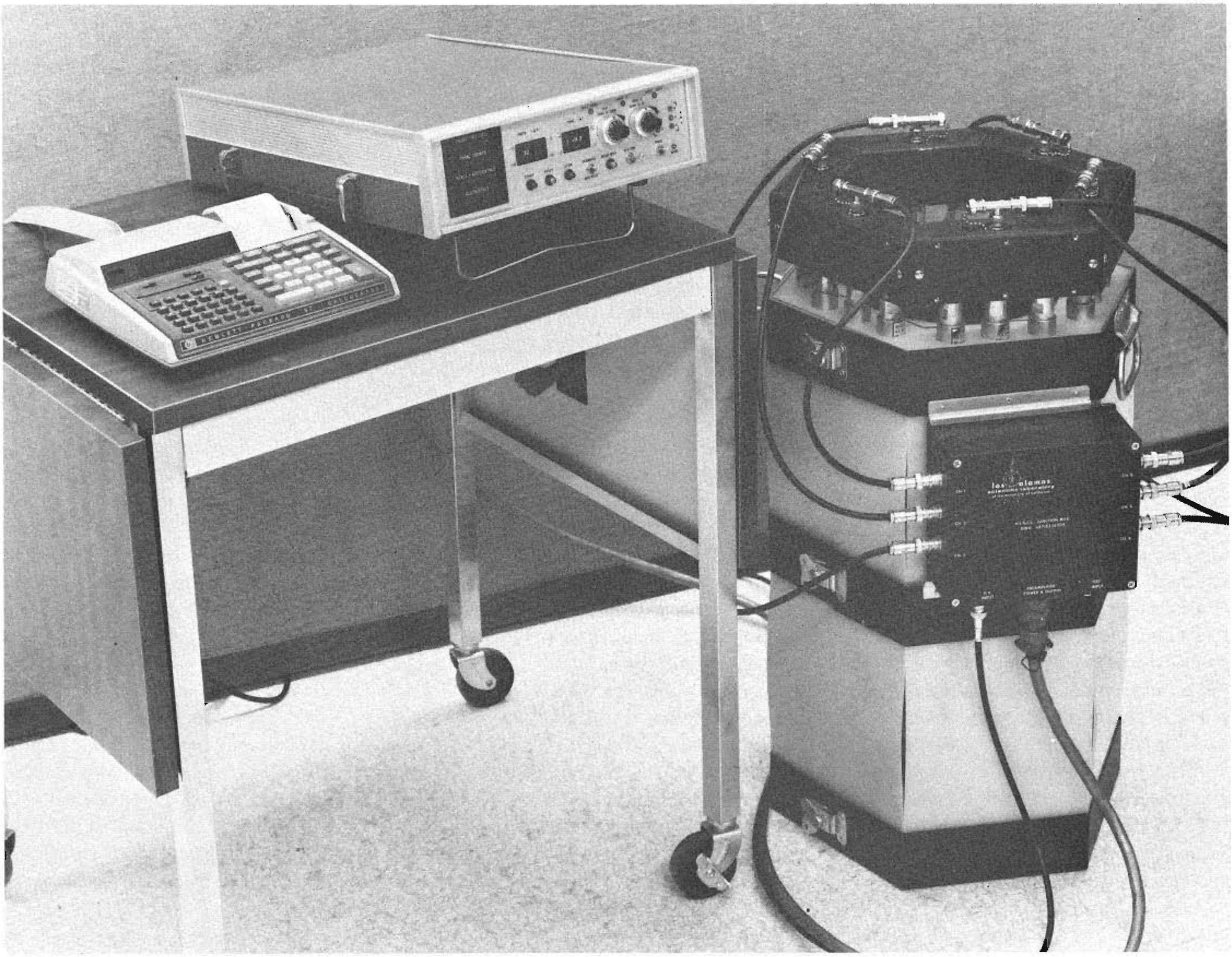
A new component in the safeguards technology transfer program at LASL is the International Training Course on Nuclear Materials Accountability sponsored by DOE in cooperation with IAEA. This course, authorized by the US Nuclear Non-Proliferation Act, was conducted May 27-June 6, 1980, at Bishop's Lodge near Santa Fe, New Mexico. The course provided to foreign governmental and institutional managers the basic knowledge needed to develop national safeguards regulations and requirements for their individual countries, and to plan toward implementation of domestic safeguards systems that will serve national needs as well as those of the IAEA International Safeguards System of inspection and verification. Lecturers for the course were experts drawn from the IAEA, United States, Canada, Czechoslovakia, Germany, and Japan. Delegates from over 25 countries participated in the course. A similar DOE/IAEA-sponsored course on the physical protection of nuclear materials is conducted by Sandia Laboratories each fall.

Emerging Impact and Role of International Safeguards

Recent expansion of the US safeguards program in areas of technical support for the IAEA and cooperative agreements with other countries reflect the growing importance of international safeguards. IAEA needs can be grouped into two major categories: (1) present requirements for portable measurement instrumentation, inspection and verification capability in direct field inspection applications (for example, the HLNCC instrument shown in Fig. 4) and (2) future requirements for methods, instruments, and techniques to be developed for independent verification of different types of advanced in-plant material accountability and control systems, such as DYMAC.

A major international effort is the TASTEX program, in which the United States, Japan, and IAEA are participating jointly in the development, test, and evaluation of advanced instrumentation and safeguards techniques at the Tokai spent-fuel reprocessing plant in Tokai Mura, Japan. In this program, a K-edge densitometer is used for nondestructive assay of plutonium nitrate product solution. The densitometer, which measures *elemental* (total plutonium) concentrations in solutions, provides a valuable complement to gamma-ray spectrometry, which measures plutonium *isotopic* composition. Successful in-plant experience with this type of new NDA instrumentation is expected to lead to the deployment of a wide range of automated NDA instruments at nuclear processing facilities. This should, in turn, provide a sound technical basis for future implementation of near-real-time material measurement and accountability systems in various types of plants and facilities throughout the nuclear fuel cycle.

As regards the outlook for the future, it is significant that this first year of the 1980s will see a number of important developments in international safeguards and nonproliferation. In March, INFCE endorsed stringently safeguarded plutonium-based nuclear energy systems



for the future, including the judicious deployment of plutonium breeder reactors (again under strict safeguards and controls) as the only means of avoiding future shortages of uranium fuel. Today the total plutonium inventory of irradiated civilian reactor fuels is easily the order of 100 metric tons and is increasing at a rate of 25-30 tons per year. Although breeder reactors eventually will reduce this inventory, concerns about such potentially large stockpiles of plutonium—in whatever form—have given rise to several international studies

Fig. 4. The high-level neutron coincidence counter (HLNCC) detects neutrons from the spontaneous fission of ^{240}Pu using ^{3}He proportional counters in a polyethylene moderator. A shift register coincidence technique is used to distinguish fission neutrons from background. The instrument is portable for use by IAEA inspectors. The electronics to operate the detectors and analyze the coincidence data are contained in the package on the table, next to a programmable calculator that is interfaced to the shift register unit.

and evaluations, involving both technical improvements and institutional arrangements, designed to place sensitive materials and fuel-cycle facilities under multinational or international control.

Proposed institutional arrangements include (1) regional fuel-cycle centers, in which large fuel reprocessing and fabrication plants would be co-located to provide economy of size and operational efficiency and to minimize vulnerability to theft and diversion; (2) an international fuel authority responsible for providing fuel service and allocating fuel resources; (3) establishment of international plutonium storage centers under IAEA control (foreseen in the Agency's Statute, Article XII, A.5); and (4) the concept of regional nuclear waste repositories, fuel reprocessing plants, and enrichment facilities under international or multinational authority. Working out the details of any such international or multinational arrangements would be a monumental task indeed, and could only be done by the potential participants themselves. With such proposals, some of them strikingly similar to the international ownership/custody/management concepts in the original Baruch plan, we have, in some sense, come almost full circle in the evolution of international safeguards.

Also in this pivotal year, 1980, two important international safeguards agreements are pending ratification by the US Senate. The first is the US-Australian Agreement on the Peaceful Uses of Nuclear Energy, the first renegotiated safeguards agreement under the new, more stringent safeguards provisions of the NNPA. The second is the US-IAEA Agreement for the Application of IAEA Safeguards in the United States, pursuant to the US 1967 offer to implement IAEA safeguards in all US facilities except those having direct national security significance. A similar voluntary agreement, already in force with the United Kingdom, is enabling the IAEA to gain valuable experience in the inspection of a fast-breeder plant and related reprocessing facility. President Carter recently asked the US Senate to take up the US-IAEA Agreement this spring so that ratification can be completed before the (potentially contentious) NPT 5-year review conference of the 116 NPT signatory nations at Geneva in August of this year. The US-IAEA Agreement, an act of good faith on the part of the United States, may help to alleviate a certain hardening of position by some countries against the NPT, which some nations view as an unequal treaty that discriminates in favor of the nuclear-weapons states and thereby against all others.

To make the NPT as equitable and acceptable as possible, the IAEA is working hard to upgrade and standardize the applications of NPT "full-scope" safeguards. Measurement and surveillance techniques used by IAEA inspectors are being improved continually both by the IAEA staff and through technical support programs of the United States and other IAEA member nations. Also, through IAEA field-inspection experience, better methods of inspection, inventory verification, reporting, and assessment are being evolved constantly to maximize inspection efficiency and effectiveness while minimizing intrusion into plant operations and production. Implementation of the US offer to place its peaceful facilities under IAEA safeguards should do much to facilitate further improvement of the IAEA system.

Another key aspect of NPT acceptability and workability is the assurance of an available supply of nuclear fuel—at present, uranium. Irrevocable fuel supply assurances are essential to the fundamental *quid pro quo* of the NPT agreement and should be extended promptly to nations that meet their nonproliferation undertakings. Uncertainties and doubts about supply assurances in recent years have had serious repercussions throughout the world nuclear community. An oft-quoted international safeguards slogan succintly states the basic *quid pro quo* of the NPT Treaty: "Irrevocable safeguards for irrevocable supply."

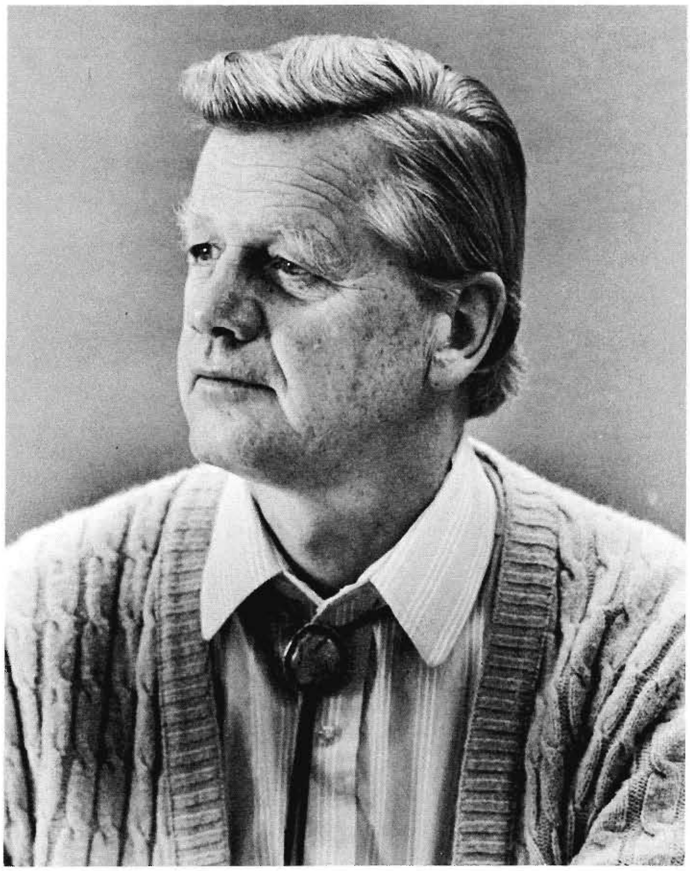
As many have pointed out (especially to safeguards technologists!), there is no question that safeguards and nonproliferation issues are first and foremost a political problem. However, it is also clear that safeguards technology development, coupled with "real world" operational experience, is indispensable in (1) providing the technical understanding and input essential to prudent planning and decision making, even at the highest political levels, and (2) providing the demonstrated technical means to implement the hardware and systems called for in those plans and decisions. Within severe budget limitations, the IAEA is making every effort to anticipate and prepare for the sophisticated fuel cycles of the future and the commensurately sophisticated technical capabilities that will be needed to carry out its essential inspection and verification functions effectively.

In concluding, I can do no better than to cite a poignant and timely question posed in a recent National Academy of Sciences report:

Which represents the greater threat to peace? The dangers of proliferation associated with the replacement of fossil resources by nuclear energy, or the exacerbation of international competition for fossil fuels that could occur in the absence of an adequate worldwide nuclear-power program.

Many hope, as I do, that this first year of the new decade will prove to be a milestone of significant progress toward worldwide implementation of effective, workable, and acceptable nuclear safeguards as an indispensable, vital contribution to safe,and safeguarded,nuclear energy for the benefit of mankind.

THE AUTHOR



G. Robert Keepin joined the LASL staff (Critical Assemblies Group) in 1952 after being an Atomic Energy Commission Postdoctoral Fellow at the University of California, Berkeley, and a Consultant to Argonne National Laboratory and to LASL. He was a US Delegate to the First United Nations Atoms for Peace Conference in Geneva in 1955, and IAEA Technical Advisor to the Third Geneva Conference in 1964.

From 1963 to 1965 Keepin was with the Headquarters Staff of the International Atomic Energy Agency in Vienna. Following his return to the United States in 1965, he established the Nuclear Safeguards research and development program at LASL. In 1973 he received a Special Award for Nuclear Materials Safeguards Technology from the American Nuclear Society for his early recognition of the need for NDA instrumentation, his demonstration of practical passive and active assay methods, and his leadership in implementing these techniques and gaining wide acceptance for their use. He is now Program Manager at LASL for Nuclear Safeguards affairs.

Keepin is a Fellow of the American Physical Society and the American Nuclear Society and is National Chairman of the Institute of Nuclear Materials Management. He is widely published in the fields of nuclear and fission physics, reactor kinetics and control, and nuclear safeguards technology, and is an internationally recognized authority in the field of nuclear safeguards and nondestructive assay technology.

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